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Single crystal as a high energy photons detector for γ-astronomy

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Abstract

One of the important problems of modern astrophysics and gamma–astronomy is in designing detectors for high energy photons (more than 1GeV) with high angular resolution. In this energy range the dominating phenomenon in interaction of photons with matter is the e^-e^+ pair production. High angular resolution can be achieved using single crystals as effective converters of photons into e^-e^+ pairs due to coherent production of pairs in the channeling regime.

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Keywords: gamma astronomy; gamma quanta; electron – positron pairs; quantum electrodynamics; chanelling

1. Introduction

One of the important problems in today's astrophysics and gamma–astronomy is the construction of high energy photons (1GeV and more) detectors with high angular resolution. In this energy range the main effect in interaction of photons with matter is the production of e^-e^+ pairs, colliding with atomic nucleus (see Fig. 1 taken from [1])

Lepton pair creation is possible when the energy of photon exceeds the doubled electron – positron energy at rest ($\hbar\omega_\gamma > 2m_ec^2$ = 1,022 MeV). When $\hbar\omega_\gamma$ >100MeV the effect of pair production in collisions with nucleus becomes dominating (see Fig. 1).

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The basic idea of the detector of high energy photons is to use some piece of solid matter as a converter of photons into e^-e^+ pairs, which are easier to register. The problem is that the cross section of pair production is rather small and rather bulky detectors are required to produce enough pairs. Another problem is the angular resolution. It is necessary to collimate the detector precisely on a certain point at the sky.

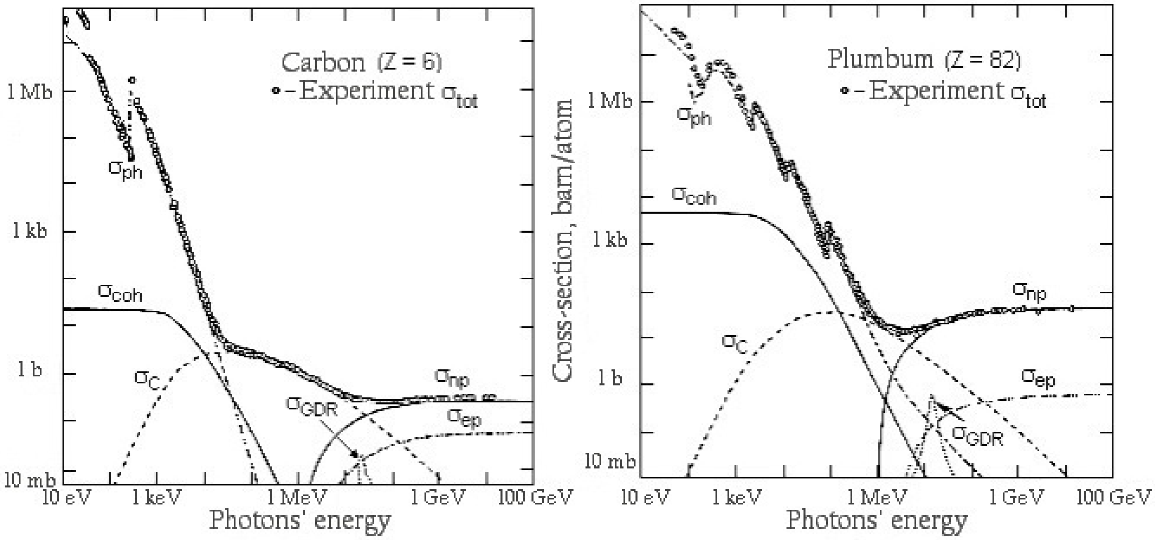


Fig.1. The cross-section of the photon interaction with matter (carbon (Z = 6) and plumbum (Z = 82)): σ_{ph} – photoeffect, σ_{coh} – Raleigh scattering, σ_C – Compton scattering, σ_{GDR} – nuclear photoabsorbtion, σ_{ep} – pair production in collisions with electrons, σ_{np} - pair production in collisions with nucleus (figure taken from [1]).

The goal of this paper is to show that both problems can be solved by using oriented single crystals as converters of high energy photons into pairs. We will present some estimations and calculations for the effectiveness of pair production in such targets.

2. Production of e-e+ pairs by high energy photons

In general, the matrix element for the pair production can be obtained from the perturbation theory [2, 3]. The first term in this row (without participating of 3-rd body) is prohibited by conservation laws in case if the wave functions of leptons are plane waves. The next two represent the second order of perturbation theory, where the atomic nucleus with the charge Ze is participating. The cross section of pair production in this order in ultra-relativistic case ($\hbar\omega_\gamma >> m_e c^2$) was first calculated by Davis, Bethe and Maximon (see [2]). If we neglect some small corrections it can be presented as

$$\sigma = (28/9)Z^2\alpha r_e^2 \ln(\hbar\omega_\gamma / m_e c^2), \tag{1}$$

where $\alpha = e^2/\hbar c = 1/137$ is the fine structure constant, $r_e = \hbar/m_e c = 3{,}86 \cdot 10^{-13}$ m is the electron Compton wavelength. The effective length to create a pair in amorphous media may be estimated as

$$L_{eff} \sim d^3/\sigma \sim a^3/Z^2\alpha r_e^2 \ln(\hbar\omega_\gamma / m_e c^2), \tag{2}$$

where a is the average inter atomic distance in the target.

In single crystals when leptons are propagating along certain crystal axis or plane they may interact with many atoms coherently that strongly influences different electromagnetic processes (see [3]). The coherent lepton pair production effect was studied theoretically and experimentally by different authors [2, 6]. It was shown that pair production can be enhanced due to coherent interaction with many atoms simultaneously.

Moreover, in ultra-relativistic case when charged particles are propagating along crystallographic axis or planes their transverse motion can be finite, and the perturbation theory for the interactions with crystal atoms stops to be applicable. This mode of motion was also studied by many authors and is known as channeling (see [2-4] and literature there),

Channeling regime becomes possible when charged particles are propagating along crystal axis or plane under the angles, smaller than the critical Lindhard angle [3]:

$$\theta<\theta_L \sim \sqrt{2U/E} \ll 1, \quad (3)$$

where E is the relativistic energy of a particle; U is the effective depth of continuous channeling potential (~20-50 eV for planar channeling in most of crystals [3]).

For pair production in ultra relativistic case the energies of the newly born particles E_{e-}, E_{e+} are comparable to the half of initial photon energy and the angles at which they will move in respect to the initial photon direction are very small $\theta_e \sim 2m_ec^2/\hbar\omega_\gamma \ll 1$ [2, 3]. If $\theta_e<\theta_L$ the leptons (one of them or both) may be born in channeling mode. The threshold condition is:

$$\hbar\omega_\gamma > m_e^2c^4/U \sim 5\text{-}10 \text{ GeV}. \quad (4)$$

Similar threshold conditions are observed for other similar processes, like the stimulated by laser beam photon production from channeling electrons [7].

3. Angular resolution of a single crystal as a gamma-photons detector.

As we have seen in case of coherent pair production it is necessary for photon to propagate along the row at the angles $\theta \leq m_ec^2/\hbar\omega_\gamma$. In case when $\theta<\theta_L \sim \sqrt{2U/E}$ – the dominating effect will be producing pairs in channeling mode. In this case the collimation angle coincides with the Lindhard angle (3). Quantitatively the expected dependence of collimation angle on the photon energy is shown on Fig. 2.

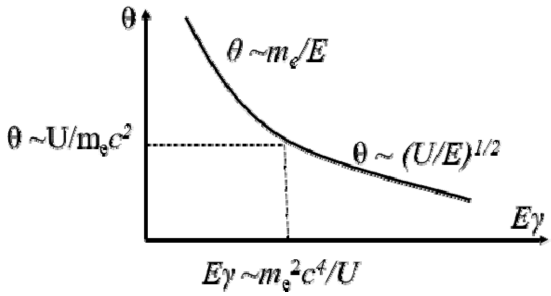


Fig.2. The dependence of collimation angle on the photon energy (quantitatively)

4. Production of e-e+ pairs by high energy photons in channeling regime.

The continuous channeling potential is obtained by averaging the potentials of atoms, constituting the crystal axis or plane [3]. In planar case it is the same as on Fig. 3.

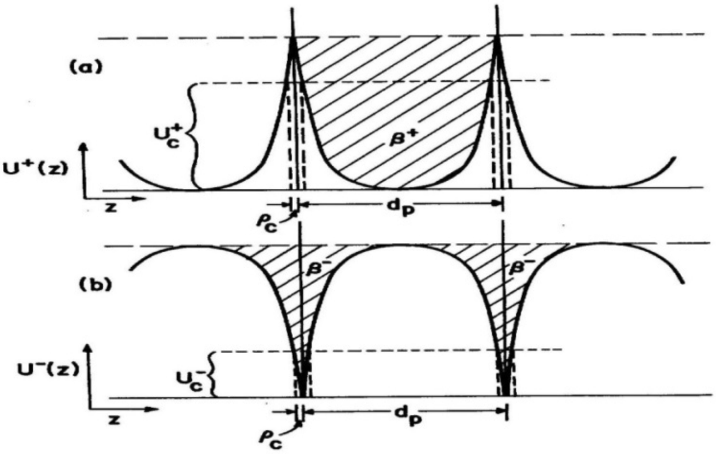
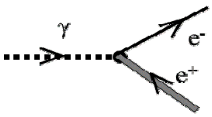


Fig.3. Schematic illustration of the planar continuum potentials for (a) positrons and (b) electrons. The shaded areas correspond to the potential wells in which channeled particles can move. U_C^+ and U_C^- are potentials evaluated at a critical distance ρ_C from a plane.

Note that for positrons the channel is broad and transverse energies in the channel E_x are positive. For electrons the channel is narrow and transverse energies are negative. When a pair is born, both particles are expected to have positive transverse energies. The probability for electron to born in a channel is low. For positrons it is high.

Production at least of one the leptons in channeling quantum state removes the ban of the process in the very first order of perturbation theory, as the wave function of channeling lepton (its transverse component) is now ***not plane wave***.



where

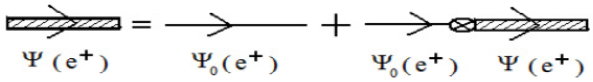


Fig.4. The scheme of pair production process, when one lepton is born in channeling regime.

The cross section for this diagram which has only one vertex will be higher than for regular pair production in the field of a nucleus. The matrix element for the diagram Fig. 4 is given by (5) in atomic units system ($\hbar = c = 1$)

$$M_{e_-e_+} = -2\pi i \frac{e}{\sqrt{2\omega}} \int \psi^{(+)*}(\overrightarrow{r}) \exp(i\vec{k}\vec{r}) \, (\vec{e}\vec{\alpha}) \psi^{(-)}(\overrightarrow{r}) \, \delta(\omega - \varepsilon_+ - \varepsilon_-) \, d^3\vec{r} \qquad (5)$$

For photon and electron we may use the plane wave functions. For positron the transverse component of the wave function $\varphi_k(x)$ must be obtained from the one dimensional Schrödinger equation with relativistic mass [3]:

$$\varphi''_k(x) + 2E(\varepsilon_k - U(x))\varphi_k(x) = 0, \qquad (6)$$

where E is relativistic lepton energy, ε_k – the allowed discrete transverse energies of the lepton in the channel with potential $U(x)$ (Fig. 3), numbered by index $k = 1,2,3\ldots$

In general to obtain the solution of this equation with proper border conditions and realistic potential $U(x)$ is a very complicated task. In [8] the approximate calculations with the model Kronig-Penny potential were presented, which had shown that the effect is possible.

For more realistic potential this work is currently in progress.

References.

[1]Review of Particle Physics. *High Energy Physics and Nuclear Physics*. *Passage of Particles Through Matter*. 2014;38:398-412.
[2]Berestetskii V. B., Lifshitz E. M., Pitaevskiĭ L.P. *Quantum Electrodynamics*. Butterworth-Heinemann. 1982. 728 p.
[3]Kalashnikov N.P. *Coherent Interactions of Charged Particles in Single Crystals.* Harwood Academic Publishers. 1988. 328 p.
[4]Ter-Mikaelyan M.L. *High energy electromagnetic processes in condensed media*. Viley-Interscience. 1972.
[5]Belkacem A., Bologna G., Chevallier M. et al. *Observation of Enhanced Pair Creation of 50-110 GeV in an Aligned Ge Crystal*. Preprint CERN–EP/84-107, 1984
[6]Baier V.N., Katkov V.M., Strakhovenko V.M. High energy electromagnetic processes in oriented single crystals. Novosibirsk: "Science" publishers (in Russian). 1989, 400 p.
[7]Kalashnikov N.P., Khangulian E.V., Olchak A.S. *NIM B. 2013;309*: 67-69.
[8]Galper A.M., Kalashnikov N.P., Mulyarchik E.I. *et al*. *Vestnik NRNU « MEPhI »* (in Russian). 2014;3(6):613-617.